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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the results of analytical and experimental investigations of both two-dimensional and one-dimensional coherent optical processors for performing space-variant operations. The two dimensional processors have generally used multiplex holography as an approach to implementing a sampling theorem-based representation of the optical system of interest. The one-dimensional processors are variations of a generalized 1-D processor which has been shown to have a variety of applications.

ABSTRACT

Both experimental and analytical investigations of coherent, space-variant optical processors have been conducted. The approach to the two-dimensional processors has been centered around the use of multiplex holography as a technique for implementing a sampling theorem-based representation of the space-variant processor. The investigation of one-dimensional processors has led to a generalized one-dimensional space-variant processor with numerous applications. A comprehensive listing of the major results obtained during the grant period is presented along with the appropriate references.

RESEARCH OBJECTIVES

The major research objectives during the period of the grant, from June 30, 1975 to September 30, 1979 have been to analytically and experimentally investigate the optical implementation of space-variant information processing operations using coherent illumination. Both two-dimensional (2-D) and one-dimensional (1-D) signal processors have been considered. The major areas of investigation have been (1) sampling theorems for space-variant systems having finite variation bandwidths; (2) the use of volume holograms for storing and playing back multiplexed holograms in a sampling theorem-based representation of such 2-D systems; (3) the use of phase-coded reference beams and thin recording media as an alternative to the volume hologram approach; (4) the correlation properties of various diffusers used to phase-code the reference beams; (5) the use of computer-multiplexed holograms as an alternative to directly-recorded multiplexed holograms for representing 2-D systems; and (6) various generalized 1-D space-variant processors and their applications. Details are provided in the following sections.

SUMMARY OF RESULTS

Due to the large number of journal publications and the two scientific reports from this research, plus the fact that the program of research is continuing under AFOSR Grant 79-0076, we will briefly summarize the major results obtained in this section, with references made to the appropriate publications and reports.

2-D Processors

Initial research under the grant was based on the concept of using the Bragg extinction angle phenomenon in a thick holographic recording medium to multiplex holograms representing the transfer functions of linear, spatially sampled space-variant optical systems so that the multiplexed holograms would only minimally interfere with each other upon playback.[1] Analytical work demonstrated that linear space-variant systems which were "variation-limited" in that their space-variant point spread functions varied spatially in a bandlimited fashion could be described rather straightforwardly in terms of a modified Whittaker-Shannon sampling theorem.[2] Thus, in principle one could spatially sample the input plane of the variation-limited space-variant system and perfectly reconstruct the output from the sampled input, at least in the absence of noise. This sampling theorem also has obvious applications to the time-variant systems of such interest in temporal signal analysis.[3]

The major problem with the approach of using volume holograms as recording media results from the fact that the Bragg extinction phenomenon is predominantly a 1-D effect, so that significant multiplexing cross-talk problems are encountered when one tries to apply the approach with 2-D inputs. An attractive alternative approach which was then discovered was to individually phase-encode each of the N reference beams used to multiplex the N stored holograms.[4,5] The required family of phase-encoding functions is required to have sharp autocorrelation functions (ideally Dirac delta functions) and small crosscorrelation functions (ideally zero) with other members of the family. The use of the phase-coding diffuser masks also means that now one does not need to use thick recording media, although the potential use of thick media for additional crosstalk noise suppression still exists.

In the laboratory we have conducted experiments with such phase-encoding diffusers as (1) shower glass; (2) ground glass, and (3) binary amplitude Gold code masks.[6] It has been found that ground glass diffuser functions, since they have the sharpest autocorrelations, are the best phase-coding diffusers. It was also observed that illumination of the diffusers with spherical rather than plane wave illumination produced superior crosstalk suppression.[5,6] These and other experimentally-observed results have been reinforced by analytical investigations[7] of the auto- and crosscorrelation properties of idealized phase and amplitude diffusers using a "random telegraph wave" diffuser model based on models commonly applied in statistical communication theory. These analytical results have shown, as expected, that pure phase diffusers are preferable to pure amplitude diffusers and combined amplitude and phase diffusers. They have also shown that one can, in principle, obtain equally good results with binary phase diffusers (two phase levels differing by 180 degrees) and multiphase diffusers (more than two possible levels) in cases where the pseudorandom phase model is "balanced" (i.e. each phase level equally likely, and the set of phase levels uniformly spanning 360^{o}). With these analytical results as encouragement, we are now continuing efforts to synthesize "quality" binary phase masks for experimental implementations. We have, however, already recorded up to 100 multiplexed holograms using ground glass diffusers with spherical ("chirped") wave illumination, and have used this approach to holographically represent an extremely space-variant distorted imaging system.[6]

One significant problem with the direct recording technique for multiplexing many holograms on a single film plate is the so called "bias buildup" problem where the bias associated with the reference beam in each of the multiple exposures contributes to a gradual using up of the linear dynamic range of the recording medium. As an alternative to this approach, we have been investigating the use of computer-generated multiplexed holograms where one performs the multiplexing of the N holograms in the computer before generating a single processing "mask" for playback.[8] Not only does this approach offer the advantages of increasing the use of the available linear dynamic range of the recording medium, but some of the crosstalk noise terms can actually be eliminated in the computer prior to the generation of the processor mask. The initial results have demonstrated the feasibility of this approach. The approach has also been used recently to code the object beams of a set of multiplexed spatial matched filters for recognizing characters which have been rotated through various angles in a scene.[9] Additional investigations are planned in this area.

A related development is this area has been the investigation of an input scanning technique for use with coherent optical processors.[10-11] In this investigation we have temporally scanned an input plane, and used the hologram plate placed in the output plane to temporally integrate the responses of the linear system to the scanning, modulated input beam, and a fixed reference beam. The initial results appear encouraging. An advantage of this approach is that one does not need a spatial light modulator at the input to a coherent optical processor, but can temporally modulate the amplitude of a spatially scanning input beam and use the time-integrating properties of the hologram at the systems' output to record and store the output of the system for future use. Marks has recently pointed out the possible applications of this result in developing a generalized 2-D space-variant coherent processor.[12]

1-D Processors

One of the results of this work has been the realization of a generalized 1-D space-variant processor.[13,14] Because a 1-D signal only requires a 2-D space-variant processing mask, whereas in principle the

2-D input requires a 4-D processing mask, the 1-D space-variant processor is much easier to realize. The basic system consists of a 1-D input, a 2-D processor mask and an astigmatic processor[15] which performs a 1-D Fourier transform along one axis, while imaging along the other axis. When one looks along one axis in the output plane, one obtains the generalized 1-D space-variant system output.[13] We have also shown that this processor can be realized with a single optical element.[14]

A related result has been that we have found that the radar ambiquity function can be achieved with a variation of this processor by utilizing the entire output plane.[16] While the ambiquity function is not, strictly speaking, a 1-D space-variant operation, this result has proven to be extremely useful to those interested in applications of coherent optical computing. Various applications of the 1-D space-variant processor have been investigated by our research group and at other institutions.[13,14,17] Methods of applying the 1-D processor results to various 2-D space-variant processing problems are also being investigated.

In summary, a large number of approaches to optically implementing 2-D and 1-D space-variant processing operations have been investigated. Although most of the investigations have utilized coherent illumination, such as from lasers, we are also investigating the use of incoherent illumination in performing space-variant processing operations. This is appropriate considering the superior noise performances and dynamic ranges characteristic of incoherent processors. It is hoped that much of the flexibility of the coherent space-variant processors described above can be realized in both continuous and discrete incoherent optical processors.

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1. L. M. Deen, J. F. Walkup, and M. O. Hagler, "Representations of Space-Variant Optical Systems Using Volume Holograms," Appl. Optics, 14, 2438 (1975).

2. R. J. Marks II, J. F. Walkup and M. O. Hagler, "A Sampling Theorem for Space-Variant Systems," J. Opt. Soc. Am., 66, 918 (1976).

3. R. J. Marks II, J. F. Walkup, and M. O. Hagler, "Sampling Theorems for Linear, Shift-Variant Systems," IEEE Trans. on Circuits and Systems, CAS-25, 228 (1978).

4. T. F. Krile, R. J. Marks II, J. F. Walkup and M. O. Hagler, "Holographic Representations of Space-Variant Systems Using Phase-Coded Reference Beams," Appl. Optics, 16, 3131 (1977).

5. T. F. Krile, M. O. Hagler, W. D. Redus, and J. F. Walkup, "Multiplex Holography with Chirp-Modulated Binary Phase-Coded Reference Beam Masks," Appl. Optics, 18, 52 (1979).

6. M. I. Jones, J. F. Walkup, and M. O. Hagler, "Multiplex Holography for Space-Variant Optical Computing," Proc. of the Society of Photo-Optical Instrumentation Engineers, Vol. 177, 16-21. Paper delivered at the SPIE Technical Symposium-East, Washington, D.C., April, 1979.

7. E. L. Kral, "Correlation Properties of Diffusers for Multiplex Holography," M. S. Thesis, Dept. of Electrical Engineering, Texas Tech University, August, 1979.

8. C. A. Irby, "Computer-Generated Multiplex Holography", M.S. Thesis, Dept. of Electrical Engineering, Texas Tech University, Dec. 1979.

9. Sing H. Lee, U. of California, San Diego. Paper presented at 1979 SPIE San Diego meeting, Aug. 1979.

10. M. O. Hagler, E. L. Kral, J. F. Walkup, and R. J. Marks II, "Linear Coherent Processing Using an Input Scanning Technique," Proc. of 1978 Internat. Opt. Computing Conf., London, England, Sept. 1978, pp. 148-152.

11. M. O. Hagler, R. J. Marks II, E. L. Kral and J. F. Walkup, "Scanning Technique for Coherent Processors," (in press, Appl. Optics).

12. R. J. Marks II, "Two Dimensional Coherent Space-Variant Processing Using Temporal Holography: Processor Theory", Appl. Optics, 18, 3670 (1979).

13. R. J. Marks II, J. F. Walkup, M. O. Hagler and T. F. Krile, "Space-Variant Processing of 1-D Signals," Appl. Optics, 16, 739 (1977).

14. R. J. Marks II, M. I. Jones, E. L. Kral, and J. F. Walkup, "One-Dimensional Linear Coherent Processing Using a Single Optical Element," Appl. Optics, 18, 2783 (1979).

15. R. J. Marks II and S. V. Bell, "Astigmatic Coherent Processor Analysis," Optical Engineering, 17, 167 (1978).

16. R. J. Marks II, J. F. Walkup and T. F. Krile, "Ambiguity Function Display: An Improved Coherent Processor," Appl. Optics, 16, 746 (1977); addendum, 16, 1777 (1977).

17. J. W. Goodman, P. Kellman, and E. W. Hansen, "Linear Space-Variant Optical Processing of 1-D Signals", Appl. Optics, 16, 733 (1977).

RECORD OF JOURNAL PUBLICATIONS ON AFOSR-75-2855

Journal Articles Published

1. L. M. Deen, J. F. Walkup and M. O. Hagler, "Representations of Space-Variant Optical Systems Using Volume Holograms," Appl. Optics, 14, 2438-2446 (1975).

2. R. J. Marks II, J. F. Walkup and M. O. Hagler, "A Sampling Theorem for Space-Variant Systems," J. Opt. Soc. Am., 66, 918-921 (1976).

3. R. J. Marks II, J. F. Walkup and M. O. Hagler, "Line Spread Function Notation," Appl. Optics, 15, 2289-2290 (1976).

4. R. J. Marks II, J. F. Walkup, M. O. Hagler, and T. F. Krile, "Space-Variant Processing of 1-D Signals," Appl. Optics, 16, 739-745 (1977).

5. R. J. Marks II, J. F. Walkup and T. F. Krile, "Ambiguity Function Display: An Improved Coherent Processor," Appl. Optics, 16, 746-750 (1977); addendum, 16, 1777 (1977).

6. T. F. Krile, R. J. Marks II, J. F. Walkup and M. O. Hagler, "Holographic Representations of Space-Variant Systems Using Phase-Coded Reference Beams," Appl. Optics, 16, 3131-3135 (1977).

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8. R. J. Marks II and S. V. Bell, "Astigmatic Coherent Processor Analysis," Optical Engineering, 17, 167-169 (1978).

9. T. F. Krile, M. O. Hagler, W. D. Redus, and J. F. Walkup, "Multiplex Holography with Chirp-Modulated Binary Phase-Coded Reference Beam Masks," Appl. Optics, 18, 52-56 (1979).

10. R. J. Marks II, J. F. Walkup, and M. O. Hagler, "Methods of Linear System Characterization Through Response Cataloging", Appl. Optics, 18, 655-659 (1979).

11. R. J. Marks II, M. I. Jones, E. L. Kral, and J. F. Walkup, "One-Dimensional Linear Coherent Processing Using a Single Optical Element," Appl. Optics, 18, 2783-2786 (1979).

12. J. F. Walkup, "Novel Techniques for Optical Information Processing: An Introduction", 18, 2735-2736 (1979).

Journal Articles in Press or Preparation

1. M. O. Hagler, R. J. Marks II, E. L. Kral and J. F. Walkup, "Scanning Technique for Coherent Processors," (in press, Appl. Optics).

2. E. L. Kral, J. F. Walkup and M. O. Hagler, "Correlation Properties of Random Phase Diffusers for Multiplex Holography," (in press, Appl. Optics).

3. M. I. Jones, J. F. Walkup, and M. O. Hagler, "Multiplex Hologram Representations of Space-Variant Optical Systems Using Ground-Glass Encoded Reference Beams," (in preparation for Appl. Optics).

4. J. F. Walkup, "Space-Variant Coherent Optical Processing", (Invited review paper, in press, Opt. Engr.).

<u>Scientific Reports</u>

1. R. J. Marks II, "Space-Variant Coherent Optical Processing," Scientific Report AFOSR-75-2855-1, Optical Systems Laboratory, Department of Electrical Engineering, Texas Tech University, Lubbock, Texas 79409, December 1, 1977.

2. M. I. Jones and E. L. Kral, "Multiplex Holography for Space-Variant Optical Processing," Scientific Report AFOSR-75-2855-2, Optical Systems Laboratory, Department of Electrical Engineering, Texas Tech University, Lubbock, Texas, September 1, 1979.

RESEARCH PERSONNEL (1975-1979)

1. Faculty

   Dr. J. F. Walkup, Principal Investigator, Associate Professor

   Dr. M. O. Hagler, Co-Principal Investigator (1975-1978), Professor

   Dr. T. F. Krile, Research Associate, Associate Professor

2. Graduate Students

   R. J. Marks II — J. M. Klingler
   S. V. Bell — C. A. Irby
   W. D. Redus — K. Rangachar
   E. L. Kral — D. S. Tavenner
   M. I. Jones

3. Undergraduate Laboratory Assistants

   K. Wong — D. Nelson
   R. Bryant — C. Lee
   J. Gilmer

COMPLETED THESES AND DISSERTATIONS (1975-1979)

1. Robert J. Marks II, "Space-Variant Coherent Optical Processing," Ph.D. dissertation, Dept. of Electrical Engineering, Texas Tech University, December 1977.

2. Wesley D. Redus, "Two-Dimensional Phase Codes for Multiplex Holography," M. S. thesis, Dept. of Electrical Engineering, Texas Tech University, May, 1978.

3. Mike I. Jones, "Multiplex Holography for Two-Dimensional Space-Variant Optical Processing," M. S. thesis, Dept. of Electrical Engineering, Texas Tech University, Aug. 1979.

4. E. Lee Kral, "Correlation Properties of Diffusers for Multiplex Holography," M. S. thesis, Dept. of Electrical Engineering, Texas Tech University, Aug. 1979.

Note: Three more M.S. theses should by completed during 1979-80 (Irby, Rangachar, Tavenner).

INTERACTION ACTIVITIES (1978-79)

A. Conference Papers Presented

1. E. L. Kral, M. O. Hagler, J. F. Walkup, and R. J. Marks II, "Input Scanning Technique for Coherent Processing", J. Opt. Soc. Am., 68, 1414A (1978). Paper presented at 1978 Annual Meeting of the Optical Society of America, San Francisco, November, 1978.

2. M. I. Jones, J. M. Klingler, M. O. Hagler, and T. F. Krile, "Implementations of Phase-Coded Reference Beams for Multiplex Holography," J. Opt. Soc. Am., 68, 1443A (1978). Paper presented at 1978 Annual Meeting of the Optical Society of America, San Francisco, November, 1978.

3. M. I. Jones, J. F. Walkup, and M. O. Hagler, "Multiplex the Holography for Space-Variant Optical Computing", Proc. of the Society of Photo-Optical Instrumentation Engineers, Vol. 177, 16-21 Paper delivered at SPIE Technical Symposium-East, Washington, D. C., April 1979.

B. Other Activities

1. Visited laboratory of Prof. J. W. Goodman at Stanford University, November, 1978 (J. Walkup, M. I. Jones, E. L. Kral).

2. Attended Joint Services Electronics Program Review at University of Southern California, and visited laboratory of Prof. A. A. Sawchuk, February, 1979 (J. Walkup).

3. Presented seminar on space-variant optical processing at Physics Department, Virginia Polytechnic Institute and State University, and visited laboratory of Prof. S. Almeida, June, 1979 (J. Walkup).

4. Presented seminar on space-variant optical processing at School of Electrical Engineering, Georgia Institute of Technology, and visited laboratory of Prof. W. T. Rhodes, June, 1979 (J. Walkup).

5. Attended 1979 SPIE Technical Symposium, San Diego, August 1979 (J. Walkup).

6. Edited feature issue of APPLIED OPTICS on "Novel Techniques for Optical Information Processing", Aug. 15, 1979 (J. Walkup).

7. Prepared invited review paper on "Space-Variant Coherent Optical Processing" for feature issue of OPTICAL ENGINEERING to be edited by Prof. D. Casasent (J. Walkup).

Note: See previous annual technical reports for lists of earlier interactions activities.

SUMMARY OF SIGNIFICANT ACCOMPLISHMENTS

1. Derivation of a sampling theorem for space-variant systems, along with various sampling theorems for other shift-variant systems.

2. Investigation of both the volume hologram approach and the phase-coded reference beam approach to multiplexing holograms for 2-D representations of space-variant systems.

3. Achieved implementations of phase-coded reference beams approach with up to 100 multiplexed holograms, using ground glass diffusers. Demonstrated the advantage of spherical ("chirped") wave illumination of the diffusers as opposed to plane wave illumination.

4. Analytically investigated the correlation properties of diffusers for multiplex holography using a spatial "random telegraph wave" model. Demonstrated the advantage of spherical wave illumination. Also showed that binary phase diffusers could perform as well as multilevel phase diffusers in suppressing crosstalk.

5. Investigated an input scanning technique for using the temporal integration properties of a hologram as a recording medium to eliminate the need for using a spatial light modulator at the input of a linear coherent optical processor.

6. Investigated the properties of a generalized space-variant coherent processor for 1-D input signals. Investigated applications of this processor.

7. Demonstrated the ability of a related 1-D processor to evaluate optically the radar ambiguity function of a real-valued 1-D input signal.